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Hydrodynamic Drag of a Flow of Steam–Water Mixture in a Pebble Bed

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Abstract—An experimental investigation is performed of hydrodynamic drag under conditions of flow of a steam-water mixture in a pebble bed for wide ranges of variation of the process parameters, namely, pressure from 0.9 to 15.6 MPa, mass velocity in the pebble bed from 107 to 770 kg/(m^2 s), and steam quality from zero to 0.48. The measurement results are given in the table. The experimental data are given in the form of the pressure loss ratio for the flow of steam-water mixture and water at the same flow rates. It is demonstrated that this quantity is in fact independent of the mass velocity and, for each fixed value of pressure, may be described by the linear function of steam quality.

INTRODUCTION

The problem of enhancement of processes of heat and mass transfer in a structurally bounded volume is topical for diverse technical applications such as thermochemical enrichment and processing of fuels in layers of catalysts, energy storage, combustion of fuel in layers, operation of gas-cooled nuclear reactors, and so on [1–3].

An efficient method of enhancement of heat transfer is by properly organizing the process of boiling of liquid in a stationary ordered granular heat-liberating layer. Detailed information about thermohydraulic characteristics of two-phase flows in a system of spherical microfuel elements is required for validation of the promising idea of using small-diameter spherical fuel elements in boiling (water-cooled) nuclear reactors.

Numerous experimental data on hydrodynamic drag and heat transfer under conditions of flow of single-phase liquid and gaseous media in pebble beds (see, for example, monograph [2]), as are presently available in the literature; however, we are not aware of similar experimental data for fixed pebble beds.

Important information is found in [4], where the results were given of an experimental investigation of hydrodynamic drag under conditions of steam-water flow in porous structures of sintered bronze particles. The experiments were performed for pressures of 0.2–0.6 MPa, mass velocity of 10 to 45 kg/(m^2 s), and steam quality of zero to unity. However, the hydrodynamic characteristics of single-phase and two-phase flows in an ordered pebble bed and in porous structures investigated by Zeigarnik *et al.* [4] may differ significantly [1–3].

Therefore, an experimental investigation of hydrodynamic drag under conditions of flow of a two-phase mixture in a pebble bed, the first stage of which was described in [5], is quite timely.

This paper, which is a continuation and further development of [5], gives the results of experiments involving hydrodynamic drag in a pebble bed under conditions of flow of air, water, and steam-water mixture in a wide range of variation of pressure, mass velocity, and steam quality.

EXPERIMENTAL FACILITY

The investigations were performed in the experimental stand described in detail in [5] (Fig. 1). The working medium (turbine condensate) was moved in a closed circuit rated for a pressure of 32 MPa and temperature up to 550 °C by a ten-plunger pump with

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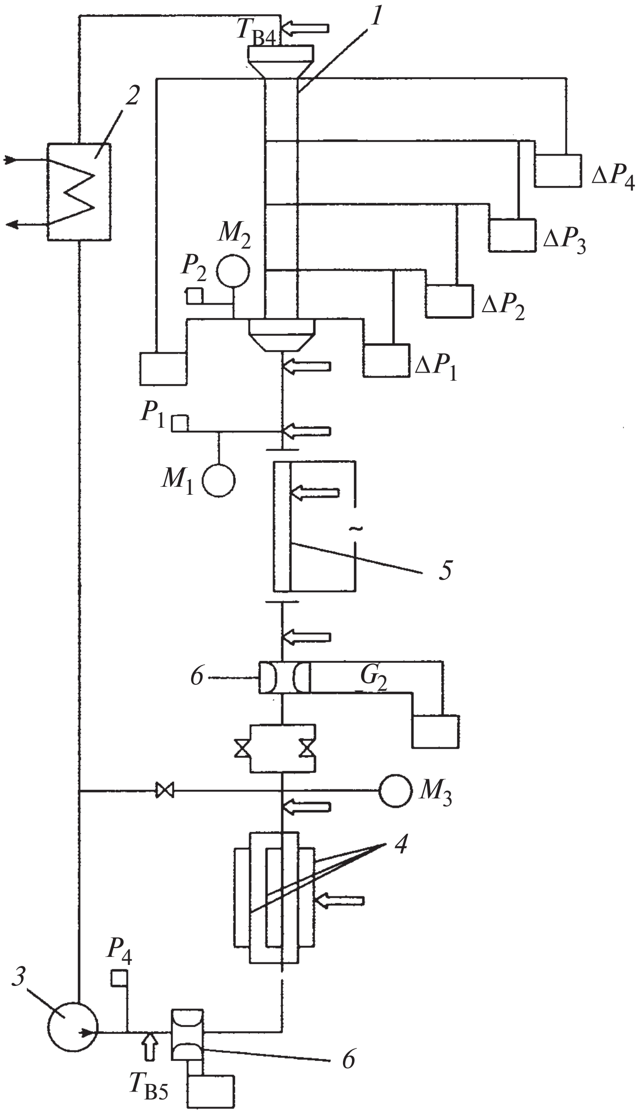

Fig. 1. A schematic diagram of the experimental stand: (*1*) experimental section, (*2*) capacitor, (*3*) circulation pump, (*4*, *5*) 360-kW and 65-kW electric heaters, (*6*) flowmeters (Venturi tube, orifice), (*7*); M_1–M_3, standard pressure gages; P_1–P_4, MPE electric pressure gages; ΔP_1–ΔP_7, Sapfir and DSE differential pressure gages.

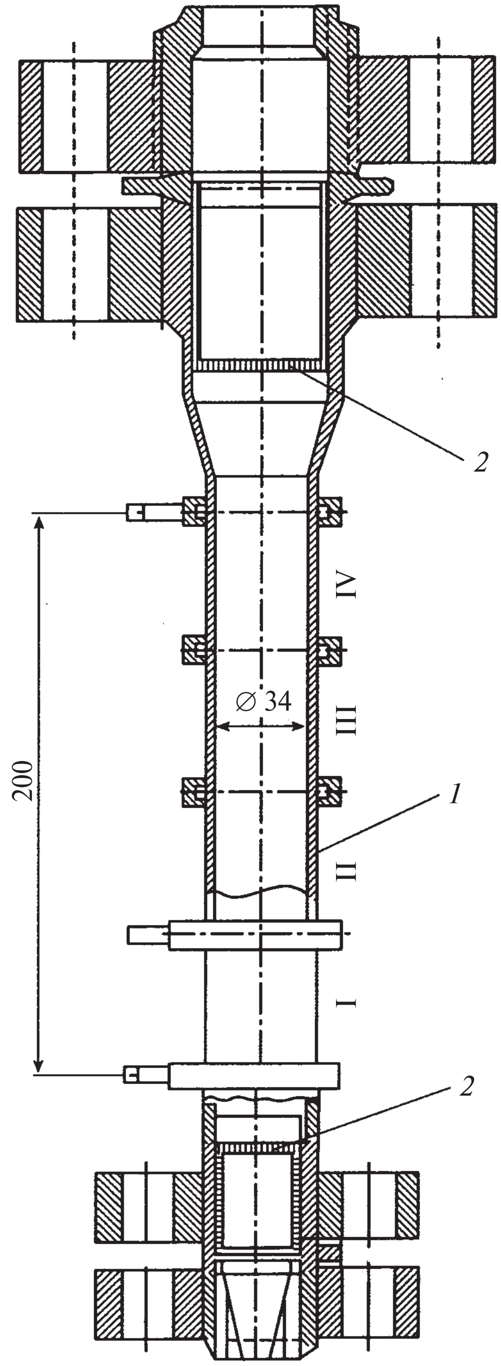

Fig. 2. Schematic of the experimental section: (*1*) working section, (*2*) top and bottom grates; I–IV, measuring sections.

a capacity of up to 25 m^3/h and maximal head of 5 MPa. The pump capacity was controlled by the number of revolutions of the engine. The required values of water temperature and steam quality of flow at the inlet to the working section were provided with the aid of upstream electric heaters of 360 and 65 kW.

Schematic of the measuring part of the circuit is given in Fig. 2. The working section was a pipe segment *1* 34 mm in diameter and 0.2 m long, divided into four measuring sections I–IV, and in distinction to the previous paper [5], was not tapered. In addition, the openings for the passage of the working medium through top and bottom grates *2* were made as slits 1.6 mm wide (in [5], they were made as round openings 1.5 mm in diameter). This made possible a significant expansion (compared to [5]) of the investigated rang-

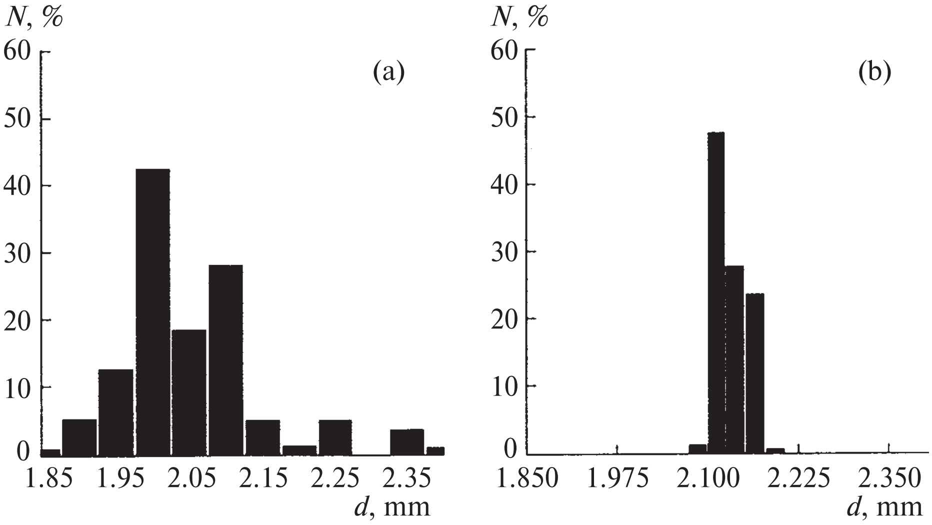

Fig. 3. Histograms of distribution of pebbles in a pebble bed with respect to diameters: (a) [5], (b) this study.

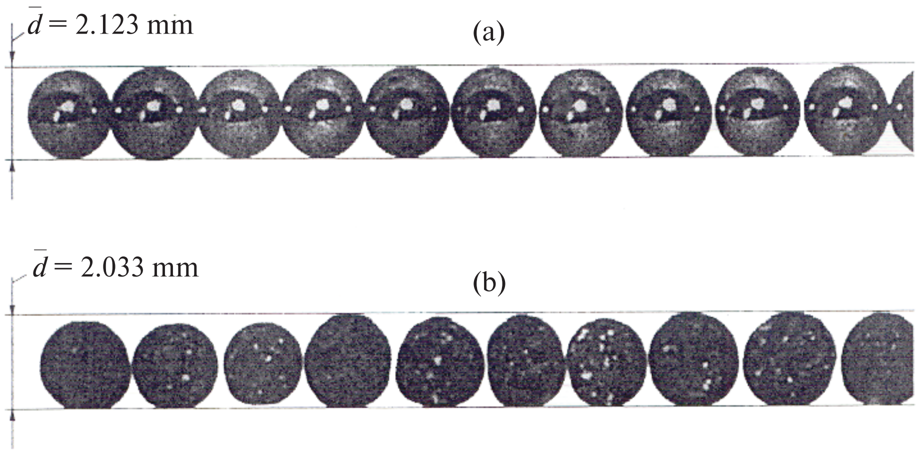

Fig. 4. Photographs of pebbles employed (a) in this study and (b) in [5].

es of mass velocity (from 237 to 770 kg/(m^2 s)) and steam quality (from 0.24 to 0.48).

In [5], lead shot (90% lead and 10% antimony) with an average diameter $\bar{d}$ = 2.033 mm was used as the pebble bed. Because of the possibility of deformation of pebbles as the temperature of the working medium approaches the melting point of lead, the pressure range to be investigated was limited to 3.3 MPa. We used polished pebbles of 25Kh13N2T (chrome-nickel-titanium) stainless steel; as a result, experiments could be performed up to pressures of 15.6 MPa.

The average value of pebble diameter ($\bar{d}$ = = 2.123 mm) was calculated as the arithmetic mean of diameters of 200 pebbles selected arbitrarily and measured by a micrometer with a scale division of 0.005 mm. Given for comparison in Fig. 3 are histograms of distribution of pebbles in the bed with respect to diameters for the previous and present series of experiments. One can see in Fig. 4, which gives photographs of pebbles of these two series of experiments, changing from lead to steel pebbles made it possible to significantly improve the uniformity of pebble bed.

Standard pressure gages (accuracy class 0.4) and MPE electric pressure gages (accuracy class 0.1) with measurement ranges from 6 to 25 MPa were used to measure the pressure at different points of the circuit. Sapfir-22 DD (class 0.5) and DSE (class 1.0) electric differential pressure gages with the measurement limits of 10 to 400 kPa were used as differential pressure cells in the working section and in flowmeters. The upper limit of measurement range of the instruments was selected such that the maximal relative error of

determination of differential pressure would not exceed ±1.5%. The error of measurement of the temperature of the heat-transfer agent by KTMS KhA (Chromel–Alumel) thermocouples (class 2.0) did not exceed ±1 K.

PROCESSING OF EXPERIMENTAL RESULTS

The cross section average porosity (volume void fraction) of pebble bed m was determined by the volumetric-weighting method and calculated by the relation

$$m = 1 - V/V_0, \tag{1}$$

where V_0 is the volume of a measuring vessel of the same diameter as the working section, and V is the pebble volume.

The measured value of porosity was $m = 0.392$ in contrast to [5] (where $m = 0.37$), which is apparently due to the asphericity of lead pebbles and nonuniformity of their size distribution. For the case of calibrated pebbles investigated by us, the volume of the batch being measured may be calculated to a high accuracy by the value of $\bar{d}$.

The flow rate of heat-transfer agent was determined by measuring the differential pressure Δp on a metering orifice of flow section F and calculated by the known formula

$$G = \alpha F\sqrt{2\Delta p \rho}, \tag{2}$$

where α is the flow coefficient, and ρ is the density of liquid.

The drag coefficient under conditions of single-phase flows of air and water in a pebble bed was determined by the relation

$$\xi = \frac{2\Delta p}{(j^2/\rho)(H/\bar{d})}. \tag{3}$$

Here, Δp is the measured differential pressure, j is the mass velocity of heat-transfer agent related to the total cross section of the experimental section, H is the height of the pebble bed between pressure taps, and ρ is the density of the medium (in experiments with air, the density was calculated by the arithmetic mean value of pressure in the test section).

The Reynolds number for a single-phase medium is

$$\mathrm{Re} = \frac{j\bar{d}}{\mu}, \tag{4}$$

where μ is the coefficient of dynamic viscosity.

The steam quality x of the flow at the inlet to the working section was determined from the heat balance by the data of measurements of electric load and thermal power of the upstream heater with due regard for the heat loss to environment,

$$x = \frac{1}{L}\left(\frac{N}{G} - c_p\Delta T - \frac{Q}{G}\right), \tag{5}$$

where N is the electrical power of the upstream preheater, Q is the heat loss, G is the mass flow rate of heat-transfer agent, c_p is the specific isobaric heat capacity of saturated water, ΔT is water subcooling at the heater inlet, and L is the specific heat of vaporization.

In order to improve the accuracy of determining the steam quality, each series of experiments with two-phase medium was preceded by experiments with subcooled water (with the same flow rate of heat-transfer agent) in which the convergence of energy balances was checked, i.e., agreement between the electrical and thermal power of the main heater. It has been found that the unbalance for the entire region of variation of process parameters does not exceed 3%.

MEASUREMENT ERROR

The relative error of determination of the volume $V_0 = (\pi d_0^2/4)H_0$ of a measuring vessel of diameter d_0 and height H_0 used for measuring the porosity of the pebble bed was 0.009, and that of the volume $V = \pi\bar{d}_0^3/6$ of a single pebble of diameter $\bar{d}$ was 0.007.

The relative error of measurement of porosity in view of formula (1) was 0.025.

The empirical formulas [1–3] for the calculation of hydrodynamic drag coefficient under conditions of flow of a single-phase medium in a pebble bed demonstrate that ξ is proportional to m to power 3–4. Therefore, the error of measurement of porosity may lead to maximal error in determining ξ which reaches $\delta\xi/\xi = 4\delta m/m \approx 0.1$.

The relative error of determination of the complex αF, which was estimated by the results of special experiment, was 0.04, and the relative error of determination of Δp was 0.015. In view of this, the maximal relative error of calculation of flow rate by formula (2) will be 0.05. Then, it follows from Eq. (4) that the relative error of determination of the Reynolds

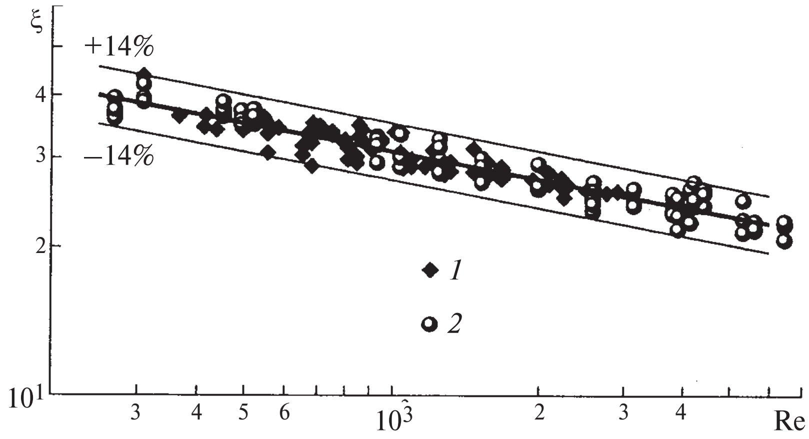

Fig. 5. The hydrodynamic drag coefficient as a function of Reynolds number under conditions of flow of (*1*) air and (*2*) water in a pebble bed.

number will be 0.05, and the relative error of determination of hydrodynamic drag coefficient will be 0.12.

Note that it was the maximal relative error of determination of quantities, which is seldom realized in practice, that was calculated above in all instances. The calculation of mean-square relative error (assuming the absence of correlation between the initial errors of quantities appearing in the calculation formula) produces much lower values. In particular, the mean-square error of determination of hydrodynamic drag coefficient is $\sigma_\xi = 0.07$.

It is known that the use of the majority of measuring systems involves the normal law of distribution of random errors. The confidence interval of these errors is determined from the condition that 95% of experimental points are located in this interval.

Given in Fig. 5 in the coordinates $\xi = f(\mathrm{Re})$ are experimental data for the case of flow of single-phase flows of air and water. Their statistical processing produces the following averaging relation:

$$\xi = \frac{112}{\mathrm{Re}^{0.186}}. \qquad (6)$$

In so doing, 95% of experimental points will lie in the interval of ±14%, which coincides with the confidence interval of mean-square error $2\sigma_\xi = 0.14$. This fact may serve as an argument for the correctness of the estimate of error of hydrodynamic drag coefficient.

Relation (6) agrees adequately with the relations given in [2]. At the same time, the values of ξ found by us are on the average 12% lower than the values obtained previously in [5]. Apparently, this difference is explained by the differences in the porosity of pebble bed. The pebble bed employed in our experiments is characterized by a much higher uniformity of size distribution of pebbles, their almost spherical shape, and a lower degree of roughness and deformability of pebbles.

It was already mentioned that the calculation of heat loss gives $Q \le 0.02N$. The relative errors of determination of N and G were $\delta N/N = 0.03$ and $\delta G/G = 0.05$, and liquid subcooling was measured with an absolute error $\delta\Delta T = 1$ K.

For the maximal investigated values of x (in fact, at $x \ge 0.3$), the first term on the right-hand side of Eq. (5) exceeds significantly the second term; as a result,

$$\frac{\delta x}{x} \approx \frac{\delta N}{N} + \frac{\delta G}{G} = 0.08. \qquad (7)$$

In the region of close-to-zero values of steam quality, the first two terms on the right-hand side of Eq. (5) almost coincide,

$$N/G \approx c_p \Delta T.$$

Then, at $x \to 0$,

$$\delta x \approx \frac{c_p \Delta T}{L}\left(\frac{\delta N}{N} + \frac{\delta G}{G} + \frac{\delta(\Delta T)}{\Delta T}\right). \qquad (8)$$

Therefore, in the region of low values of x, the maximal absolute error of determination of steam quality increases with decreasing specific heat of vaporization (i.e., with increasing pressure), as well as with increasing subcooling of liquid at the inlet to the heater. The calculation by formula (8) for minimal values of investigated steam quality ($x \le 0.025$) at $p = 14.6$ to 15.6 MPa gives $\delta x \approx 0.01$. In the case of decreasing pressure, the error will decrease and, at $p = 2.0$–3.0 MPa, it will amount to $\delta x \approx 0.005$. There-

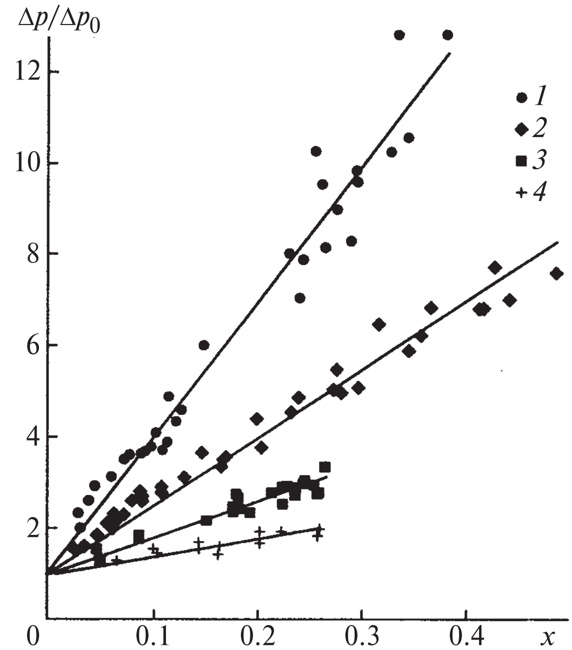

Fig. 6. The relative pressure loss under conditions of flow of a steam-water mixture in a pebble bed as a function of steam quality: (*1*) p = = 14.6–15.6 MPa, (*2*) p = 8.4–10.4 MPa, (*3*) p = = 4.6–5.6 MPa, (*4*) p = 2.0–3.0 MPa.

fore, for low values of steam quality, the error of determination of x may be crude, and this possibility must be taken into account in analyzing the experimental points obtained under these conditions.

DISCUSSION OF THE RESULTS

In view of the large number of obtained experimental data, the table gives the most typical experimentally obtained values.

The measurement results are given in Fig. 6 in the form of $\Delta p/\Delta p_0 = f(x)$ which is conventional for two-phase flows. Here, Δp is the loss of pressure in a two-phase flow, Δp_0 is the loss of pressure in a flow of saturated liquid with the same mass flow rate, and x is the steam quality average over the test section. The value of Δp_0 was determined from Eq. (6) which averages the experimental data on hydrodynamic drag for a single-phase flow.

In order to reveal the effect of pressure, the experimental data were divided into four groups, namely, those of 2.0–3.0 MPa, 4.6–5.6 MPa, 8.4–10.4 MPa, and 14.6–15.6 MPa. It follows from Fig. 6 that the relative pressure increases with increasing steam quality and decreasing pressure.

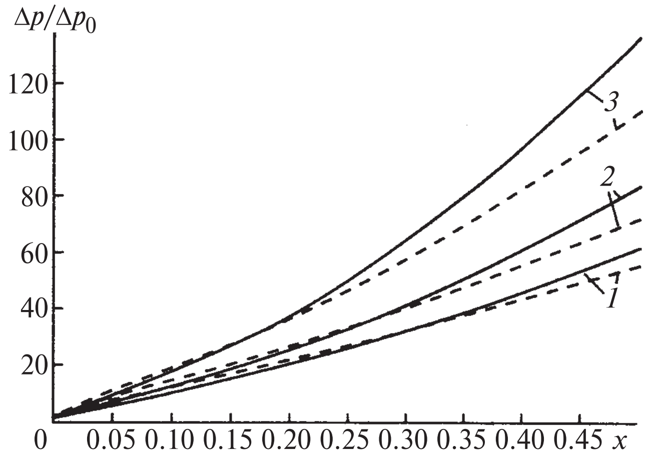

Fig. 7. The relative pressure loss under conditions of flow of a steam-water mixture in a porous structure as a function of steam quality. Calculation by the formulas of [4]; (*1*) p = 0.59 MPa, (*2*) p = 0.4 MPa, (*3*) p = 0.2 MPa; solid line indicates j = 27 kg/(m^2 s), and dotted line indicates j = = 13 kg/(m^2 s).

One can see in this figure that the experimental data in the investigated range of variation of process parameters at fixed pressure are approximated by linear dependences $\Delta p/\Delta p_0 = f(x)$ which are in fact invariant relative to the mass velocity. In so doing, the scatter of data, which is especially significant at low pressures, is largely attributed to the stratification of experimental points with respect to pressure within the respective interval.

As was mentioned above, no experimental data are available in the literature on hydrodynamic drag under conditions of two-phase flows in fixed pebble beds. Therefore, it is of interest to compare the results of our experiments with the results of Zeigarnik and Kalmykov [4] for the case of steam-water flow in porous structures of sintered bronze particles.

Unfortunately, it does not appear possible to compare directly these groups of data both because of differences in the investigated range of variation of process parameters (Zeigarnik and Kalmykov [4] performed their measurements at pressures of 0.2–0.59 MPa and mass velocities up to 27 kg/(m^2 s)) and because of different properties of the porous systems being studied. The semiempirical recommendations of Zeigarnik and Kalmykov [4] are based on the Darcy equation for single-phase flow, which does not make it possible to produce an adequate description of flow in a pebble bed.

Hydrodynamic drag under conditions of flow of a steam-water mixture in a pebble bed (D = 34 mm, $\bar{d}$ = 2.123 mm, H = 200 mm, m = 0.392)

No. of experiment	p_{in}, MPa	G, kg/s	Δp, kPa	$\Delta p/\Delta p_0$	x
1	1.61	0.114	90.35	3.44	0.0560
2	1.637	0.171	105.8	1.92	0.0145
3	1.666	0.167	108.8	2.17	0.0251
4	1. 725	0.159	118.6	2.57	0.0340
5	1. 813	0.150	122.5	2.93	0.0444
6	1. 901	0.146	123.5	3.07	0.0514
7	1. 754	0.140	134.3	3.65	0.0657
8	1. 921	0.133	131.3	3.95	0.0782
9	1. 891	0.220	137.2	4.68	0.0890
10	2.068	0.158	71.54	1.72	0.0150
11	2.205	0.109	49.98	2.32	0.0300
12	2.303	0.154	80.36	2.00	0.0315
13	2.313	0.143	109.8	3.12	0.0610
14	2.009	0.146	131.3	3.60	0.0770
15	2.058	0.152	144.1	3.66	0.0930
16	2.215	0.153	161.7	4.08	0.1035
17	2.381	0.153	155.8	3.88	0.1130
18	2.009	0.125	133.3	4.88	0.1150
19	2.509	0.143	155.8	4.55	0.1270
20	1. 891	0.220	137.2	1.67	0.0127
21	1.666	0.221	149.0	1.95	0.0225
22	1. 774	0.226	211.7	2.68	0.0372
23	1. 921	0.225	204.8	2.61	0.0386
24	1. 832	0.219	204.8	2.73	0.0404
25	1. 911	0.220	222.4	2.92	0.0455
26	1. 911	0.216	232.3	3.17	0.0548
27	1. 852	0.206	225.4	3.36	0.0578
28	4.478	0.126	73.5	2.31	0.0625
29	4.478	0.126	73.5	2.31	0.0625
30	4.714	0.122	78.4	2.59	0.0799
31	4.89	0.124	78.99	2.58	0.0892
32	5.36	0.133	95.06	2.95	0.0160
33	4.439	0.159	65.58	1.60	0.0355
34	4.616	0.147	80.36	2.12	0.0630
35	4.821	0.140	97.02	2.77	0.1080
36	4.978	0.149	140.14	3.62	0.1470
37	5.184	0.152	139.16	3.35	0.1660
38	5.194	0.132	112.7	3.58	0.1685
39	4.88	0.167	112.7	2.15	0.0615
40	5.233	0.154	122.5	2.69	0.0905
41	5.106	0.220	134.3	1.56	0.0260
42	5.155	0.212	154.8	1.86	0.0458
43	8.986	0.129	47.04	1.45	0.0470

End

No. of experiment	p_{in}, MPa	G, kg/s	Δp, kPa	$\Delta p/\Delta p_0$	x
44	9.476	0.133	62.72	1.83	0.0910
45	10.143	0.153	100.9	2.25	0.1530
46	9.545	0.149	108.8	2.42	0.1770
47	9.643	0.144	113.7	2.87	0.2230
48	9.369	0.109	70.56	2.98	0.2290
49	10.231	0.141	109.8	2.82	0.2380
50	9.839	0.138	112.7	2.96	0.2450
51	11.583	0.243	146.0	1.37	0.0040
52	12.064	0.233	159.7	1.62	0.0820
53	12.75	0.212	156.8	1.88	0.1320
54	12.74	0.219	162.7	1.83	0.1370
55	12.563	0.107	48.02	1.94	0.1410
56	12.681	0.154	114.7	2.72	0.2160
57	12.505	0.114	62.72	2.25	0.2300
58	12.495	0.120	79.38	2.66	0.2980
59	12.651	0.110	73.50	2.72	0.3010
60	9.780	0.111	31.06	1.26	0.0264
61	9.427	0.110	44.10	1.82	0.0870
62	8.947	0.091	44.88	2.63	0.1810
63	8.702	0.095	43.51	2.37	0.1830
64	10.09	0.108	53.90	2.29	0.1930
65	9.467	0.106	61.25	2.74	0.2130
66	10.01	0.106	58.50	2.53	0.2230
67	9.780	0.102	61.84	2.90	0.2550
68	10.035	0.104	59.68	2.72	0.2580
69	8.947	0.090	56.15	3.33	0.2650
70	14.308	0.104	31.16	1.29	0.0650
71	14.308	0.101	35.28	1.54	0.1000
72	14.847	0.103	34.89	1.45	0.1050
73	14.259	0.105	40.57	1.65	0.1435
74	15.16	0.103	38.41	1.58	0.1630
75	14.55	0.099	41.75	1.89	0.2010
76	14.308	0.107	48.51	1.92	0.2220
77	15.043	0.106	48.70	1.94	0.2520
78	15.288	0.100	45.77	1.98	0.2580

Nevertheless, analysis of the recommendations of [4] is of significant interest. Figure 7 gives the dependences $\Delta p/\Delta p_0 = f(x)$ calculated by the formulas of [4] at different pressures for the maximal (j = = 27 kg/(m^2 s)) and minimal (j = 13 kg/(m^2 s)) values of mass velocity. Note that Zeigarnik and Kalmykov [4] varied the mass flow rate only in the series of experiments performed at a pressure of 0.59 MPa.

One can see in Fig. 7 that the stratification of the calculation results caused by variations of mass velocity in the range of $0 \le x \le 0.5$ was not too significant, and the dependence $\Delta p/\Delta p_0 = f(x)$ approaches a linear pattern as the pressure increases.

The simplest of the known computational schemes is the procedure based on the homogeneous model of two-phase mixture, which leads to the following ratio for relative pressure losses:

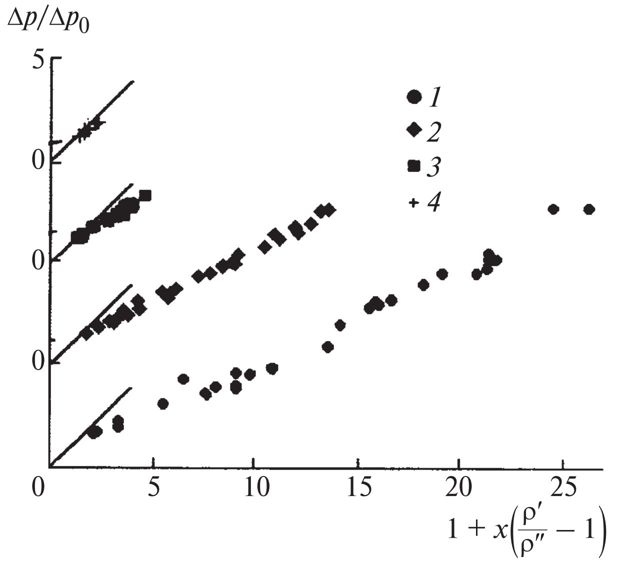

Fig. 8. Comparison of the experimentally obtained values of relative pressure loss with those calculated by the homogeneous model under conditions of flow of a steam-water mixture: (*1*) $p = 14.6–15.6$ MPa, (*2*) $p = 8.4–10.4$ MPa, (*3*) $p = 4.6–5.6$ MPa, (*4*) $p = 2.0–3.0$ MPa.

$$\frac{\Delta p}{\Delta p_0} = 1 + x\left(\frac{\rho'}{\rho''} - 1\right). \quad (9)$$

Here, ρ' and ρ'' denote the liquid and gas density, respectively.

One can see in Fig. 8 that the dependences $\Delta p/\Delta p_0 = f(x)$ in our case differ significantly from those calculated by the homogeneous model; as the pressure decreases, the divergence increases.

Note in conclusion that the array of experimental data obtained by us will form a basis for the development of theoretical models of flow of a steam-water mixture in stationary pebble beds, as well as of theoretical recommendations.

CONCLUSIONS

The previous study [5] has been continued by an experimental investigation of hydrodynamic drag under conditions of flow of a steam-water mixture in a fixed pebble bed for wide ranges of variation of the process parameters (pressure from 0.9 to 15.6 MPa, mass velocity from 107 to 770 kg/(m^2 s), and steam quality from zero to 0.48.

Changing from lead to calibrated steel pebbles made it possible to significantly improve the uniformity of pebble bed.

It has been found that the relative pressure loss of two-phase flow is in fact independent of the mass flow rate and, for each fixed value of pressure, is approximated by the linear functions of steam quality.

The relatively simple form of the experimentally obtained dependences leads one to assume the possibility of constructing physical models of two-phase flows in pebble beds and using these models to produce final theoretical recommendations.

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